REPORT 249-7

THE USE OF OBLIQUE SOUNDING FOR PROPAGATION ANALYSIS AND OPTIMIZATION

(Study Programme 27B/6)

(1959-1963-1966-1970-1974-1978-1982-1986-1990)

1. Introduction

This report is concerned with the use of oblique sounding for the analysis of propagation conditions on a fixed point-to-point circuit, and for the real-time selection of the optimum working frequency (OWF). Evaluation of an HF circuit benefits from knowledge of the propagation modes, and the time delay and Doppler spread on each mode, as a function of frequency. Applications of the techniques described in this Report for real-time circuit evaluation are contained in Report 889.

2. Techniques

Measurement of mode structure can be achieved by step-frequency pulse or swept-frequency (FMCW) transmissions, the latter offering the advantage of low peak power requirements [Fenwick and Barry, 1965]. Oblique sounding is a very powerful technique for the study of propagation conditions along a fixed point-to-point circuit, and has been used to provide test data for the validation of MUF prediction techniques, for the identification of unusual propagation modes, and other purposes which rely on the large amount of detailed information shown on an oblique ionogram. Long-range propagation experiments using oblique digital ionosondes have measured polarization, amplitude, phase, Doppler frequency and incidence angle [Reinisch et al., 1985].

The conventional oblique incidence ionosonde does not measure Doppler characteristics. Although it is possible to measure Doppler spread on a CW transmission, it is generally not possible to resolve the contribution from individual modes. The time-delay spread and Doppler spread on each mode can be measured using narrow-band FMCW [Earl and Ward, 1987] or a coded-pulse sounder utilizing a real-time correlation receiver [Wagner and Goldstein, 1985].

3. Results of propagation analyses

Oblique incidence pulse tests have been undertaken in Canada [Hatton, 1961], France [Delobeau *et al.*, 1955], Federal Republic of Germany [Möller, 1960], Japan [Aono, 1962], the United States of America [Agy and Davies, 1959; Tveten, 1961] and in Africa [Davies and Barghausen, 1966].

Many oblique measurements have been made, some of which have been scaled for the maximum observed frequency (MOF), over HF circuits in various parts of the world during a range of solar activity conditions between 1981 and 1988 [Goodman and Daehler, 1988].

3.1 MUF versus MOF comparison

Care must be exercised when comparing maximum observed frequencies (MOF) with predicted MUFs to establish whether any differences arise due to the ionospheric mapping or from the application of the obliquity factor. Comparison of maximum observed frequencies with predicted MUFs has shown that the existing theories of propagation generally seem to be adequate for calculating the basic MUF for distances up to several thousands of kilometres.

McNamara [1975] found that for two 2000-km circuits within Australia, monthly median predicted 1-hop MUFs were within about 5% of the MOF. For 2- and 3-hop propagation modes, the discrepancies were larger, partially as a result of the simplifying assumptions in the method used for MUF calculations (equal hop length, no tilts).

The maximum and lowest observed frequencies (MOF and LOF), as well as the parts of the spectrum having the least multipath propagation and the active propagation modes, were observed on 5 paths in the USSR with ranges between 1000 km and 10 000 km [Smirnov, 1972]. In quiet ionospheric conditions the MOF usually exceeded the basic MUF, which was calculated using the USSR prediction method [Zhulina *et al.*, 1969], by 10 to 35%. The increase in the MOF caused by scatter amounted to about 10%. In periods of magnetic disturbance the MOF was less than the basic MUF and the LOF increased. Additional studies have been reported [Rose *et al.*, 1978] using 132 path-months of hourly median MOF.

Measurements of MUF over HF circuits in the north-eastern United States of America have been made during part of the solar cycle maximum and agree well with values predicted by ITS-78 and IONCAP prediction programs [Teters *et al.*, 1983; Millman and Swanson, 1985]. Daehler et al., [1987] and Roy and Sailors [1987] have compared MUFs predicted by several propagation models with MOFs for numerous paths.

There can be notable departures between calculated and observed results if calculations are made using simple theoretical models. This agreement can be improved by the inclusion of electron density gradients in ray tracing [Röttger, 1967] and modelling horizontal gradients [Davies and Rush, 1985]. Angle of arrival measurements may, in principle, determine the extent to which gradients must be taken into account.

It is extremely important when comparing MUFs and MOFs for each propagation mode be scaled separately so that MOFs and MUFs are compared for the same propagation mode. If the MOF data are tabulated without regard to mode, they should be analysed in terms of histograms of count versus MOF. This allows the identification of the propagation modes present. Median values calculated without regard to the number of propagation modes present in the observed data can be very misleading [McNamara, 1974].

3.2 Study of anomalous propagation modes

The presence of anomalous propagation modes on a given circuit can be established either by comparing the observed oblique ionograms with simulated ionograms for all the usual propagation modes, or by comparing reliable MUFs with the hourly histograms of the MOF. Either method can reveal a propagation mode with an MOF higher than the highest predicted MUF. The extra propagation mode could correspond, for example, to Es modes, to combination modes involving equatorial Es [McNamara, 1974] or to either of the two trans-equatorial propagation (TEP modes) [Nielson and Crochet, 1974; McNamara, 1974].

In an experiment carried out in 1970 and 1971 between Japan and Australia, for the path distances of 5873 km [Kuriki et al., 1974] and 7374 km [Tanohata et al., 1975], the dominant mode of propagation involves two reflections from the F layer with an intervening reflection at the surface of the Earth (2F mode). However, signals at frequencies higher than the maximum observed frequency of the 2F mode were frequently received during the period around 1000 to 2000 h local time. The occurrence was about 40% for each hour of observation and the MOF of this mode was about 4 ± 2MHz higher than the MOF of the 2F mode propagating at the same time.

At low latitudes anomalously high operational MUFs associated with F scatter are encountered at night [Davies and Barghausen, 1966; Nielson and Crochet, 1974].

For high-latitude paths, the basic MUF for transmission distances at the 2000-3400 km range is normally controlled by the F1 layer in the summer [Petrie and Stevens, 1965]. For long paths, the one hop F2 (Pedersen ray) is the principal mode [Hagg and Rolfe, 1963] under certain conditions over a wide range of latitudes. The maximum observed frequency (MOF) may however be controlled by an Es mode on some occasions. Further results of high latitude soundings were presented in a survey paper [Hunsucker and Bates, 1969].

The reflection coefficient of Es and the ionosonde equipment characteristics must be considered in estimating the usefulness of Es as a reflector at oblique incidence [Stevens, 1968a]. Sporadic-E MOFs for one-hop auroral region paths as high as 72 MHz are implied from simultaneous incoherent scatter radar and ionosonde data [Hunsucker, 1975].

Anomalous propagation modes affecting VHF propagation are described in Report 259.

3.3 Magneto-ionic splitting

Magneto-ionic splitting of x and o components was studied by Kopka and Möller [1968] using ray tracing. Results are given for a 2000 km path as a function of both magnetic latitude and magnetic azimuth. In general, the magneto-ionic splitting is less for an east-west path than a north-south path. Aono [1962] and Davies and Barghausen [1966] found this separation to be nearly equal to the longitudinal value of the gyrofrequency f_H on north-south paths. Agy and Davies [1959] found that there was a separation of about 0.2 MHz on a 2400 km east-west path and that the separation decreased with an increase in distance.

3.4 Characteristics of multipath propagation

Sweep-frequency pulse sounding results show that the spread of time delays due to multipath propagation decreases with increasing ratio, K (working frequency/basic MUF). Numerical data are given, for a variety of paths, by Davies [1965]. Measurements in China [Chen and Zhou, 1984] on a 1340 km path show that for $K < 1$, the mean spread exhibits a parabolic decrease as K increases, with a minimum value at $K = 1$, while for $K > 1$ up to the operational MUF the mean spread is unchanged. Theoretical analysis [Dai, 1985] shows that for a given value of K, the spread is normally distributed and that the expectation and variance vary with the value of K. This was confirmed by the above measurements.

Propagation experiments conducted during the period November-December 1981, along a great-circle path from north to south over 11 000 km, show that the frequency range of single-mode propagation becomes widest at a propagation distance of about 2000-3500 km, and then decreases gradually with an increase in distance. Single mode propagation at distances greater than about 8000 km is difficult to identify because many complex modes appear at the same frequency [Ichinose *et al.*, 1985].

The time-delay data necessary to simulate the HF channel (see Report 549) in the design of wideband communications systems can be obtained from oblique-incidence ionograms. However, the resolution in time delay in some sounder systems may not be adequate to allow the data to be used effectively [Sailors and Hill, 1977].

3.5 Channel scattering function

A wideband, step frequency coded pulse channel probe has been used to evaluate propagation conditions on high latitude paths [Wagner et al., 1987]. Pulse response time ———— diagrams and channel scattering functions constructed from the data permit individual propagating modes to be classified as specular, multipath-specular, or diffuse multipath. Short range propagation experiments using a coherent, coded-pulse oblique sounder designed to probe the HF communication channel to a bandwidth of 1 MHz, have been conducted [Wagner and Goldstein, 1985]. Such experiments yield measurements of the amplitude, the phase, the delay dispersion and the group delay.

Other high latitude channel probe measurements [Basler et al., 1987] have been used in conjunction with a theoretical model to determine the characteristics of the ionosphere responsible for the observed time-delay and Doppler spread.

4. Application to practical HF communication links

Results from oblique incidence sounding studies have shown that such equipments may be used in parallel with communications systems to determine optimum, short-term operating frequencies. A number of studies have now been carried out which are designed to determine the improvements that can be achieved from the use of oblique sounding information [Probst, 1968; Stevens, 1968b; Slutz *et al.*, 1969].

Improvement in radiocommunications during disturbed propagation conditions has been achieved due to effective selection and use of available operating frequencies when predictions or prearranged operating frequency schedules are inaccurate [Jull *et al.*, 1962].

It has been found that oblique sounding information can be a valuable aid in assessing the performance of the communication system. With propagation removed as an unknown variable, any defects in, or limitations of, the communication system performance or operation can be more readily discovered.

However, experiments involving ionospheric sounding at oblique incidence disclose a number of problems when the sounding equipment is used in parallel with the communications equipment or when the communications equipment is used to perform the sounding. The following must be considered:

- any differences in operational sensitivity between communication and sounding equipment parameters;
- inaccuracies which result from sounding over an ionospheric path separated from the communications path (particularly when the sounding data are used for quantitative prediction of signal levels). Studies [Jull, 1968] suggest that for a separation of 32 km, the r.m.s. differences in signal levels amounted to 5 dB when the sounding information was averaged over eight minutes;
- that ionospheric non-reciprocity results in unequal levels of signals travelling in opposite direction between linear antennas. The path non-reciprocity which arises when polarization fading was present can be appreciably reduced by averaging signal levels for eight minutes [Jull, 1968];
- any differences of performance of the sounder and communication equipment in the presence of interference;
- the difficulty in determining the sounding repetition rate required to ensure the validity of the information when ionospheric conditions begin to vary, as during disturbed periods;
- the difficulty in determining a sounding signal that is representative of the modulation of the communications system;

Operational applications of the HF oblique incidence sounding are treated by Study Group 3 (see Report 357). Oblique ionosondes are the most widely used form of class I real-time channel evaluation systems (see Report 889). However, other techniques offer considerable potential.

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